

# The Fermilab Quark Flavor Program

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# The On-going and Near-term Program of CPV and CKM related studies

- KTeV and NA48 have made a major advance in reducing the statistical and systematic uncertainties in  $\epsilon'/\epsilon$  and other CPV decays
- BaBar and Belle have conclusively established CP violation in B decays through their measurement of values of  $\sin 2\beta$  that are many  $\sigma$  from zero. They will continue to pursue CP violation in B decays in  $B_d$  and  $B_u$  for many years, eventually limited by the limited number of B's they have
- Fermilab: Run II is expected to bring new results on  $B_s$  mixing and CP violation studies in a variety of  $B_{d/u}$  and  $B_s$  final states from CDF and D0

**This is an exciting area! Real progress is being made! After this phase, there will still be much work to be done and that is where two new experiments BTeV and CKM come in.**

## Wolfenstein Parameterization of the CKM Matrix

The CKM Matrix describes the mixing of the charge 1/3 quarks, here to 3rd order in  $\lambda$  for real part and 5th order in imaginary part

$$\begin{pmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3(r - ih\left[1 - \frac{1}{2}\lambda^2\right]) \\ -\lambda & 1 - \frac{1}{2}\lambda^2 - ihA^2\lambda^4 & A\lambda^2(1 + ih\lambda^2) \\ A\lambda^3(1 - r - ih) & -A\lambda^2 & 1 \end{pmatrix}$$

$\eta$  is the imaginary piece of the CKM elements  $V_{td}$  and  $V_{ub}$ .

**According to the SM,  $h$  is responsible for CP violation, in both Kaon and B (and all other) decays.** The smallest number of generations for which unitarity permits a weak phase is three generations.

**Is this description right? Is it complete? Physics beyond the Standard Model could cause deviations from this picture.** 3

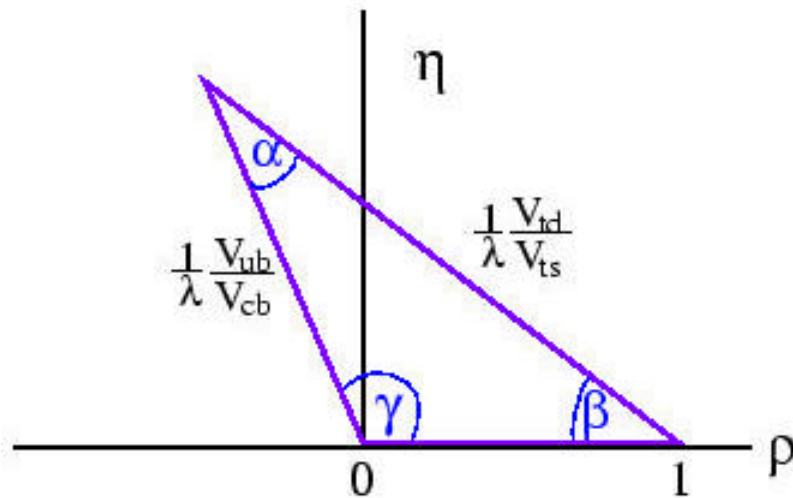
# From “recent” B physics Workshops

- The Standard Model of CPV is **unique, predictive, and testable**
- CPV is one of the **LEAST TESTED** aspects of the Standard Model
- Almost any **EXTENSION** of the Standard Model **has new sources of CPV**
- The observed **baryon asymmetry of the universe requires new sources of CPV** (not necessarily at this scale, though)

It is “possible, likely, **unavoidable**” that the SM picture of CPV is incomplete. CPV is an excellent probe for new physics. It is testable.

**Conclusion: challenge SM CPV on every front. For Fermilab, this means an attack on both the Kaon and B fronts**

# Key Measurements of the CKM matrix in B Decays



$$\mathbf{c} = \arg\left(-\frac{V_{cs}^* V_{cb}}{V_{ts}^* V_{tb}}\right)$$

Physics Quantity	Decay Mode
$\sin(2\alpha)$	$B^0 \rightarrow \rho\pi \rightarrow \pi^+\pi^-\pi^0$
$\cos(2\alpha)$	$B^0 \rightarrow \rho\pi \rightarrow \pi^+\pi^-\pi^0$
$\text{sign}(\sin(2\alpha))$	$B^0 \rightarrow \rho\pi, B^0 \rightarrow \pi^+\pi^-$
$\sin(\gamma)$	$B_s \rightarrow D_s K^-$
$\sin(\gamma)$	$B^+ \rightarrow D^0 K^+$
$\sin(\gamma)$	$B \rightarrow K\pi$
$\sin(\gamma)$	$B \rightarrow \pi^+\pi^-, B_s \rightarrow K^+K^-$
$\sin(2\chi)$	$B_s \rightarrow J/\psi\eta', J/\psi\eta$
$\sin(2\beta)$	$B^0 \rightarrow J/\psi K_s$
$\sin(2\beta)$	$B^0 \rightarrow \phi K_s, \eta' K_s, J/\psi\phi$
$\cos(2\beta)$	$B^0 \rightarrow J/\psi K^*, B_s \rightarrow J/\psi\phi$
$x_s$	$B_s \rightarrow D_s\pi^-$
$\Delta\Gamma$ for $B_s$	$B_s \rightarrow J/\psi\eta', K^+K^-, D_s\pi^-$

About 1/2 of the key measurements are in  $B_s$  decays!  
 About 1/2 of the key measurements have  $p^0$ 's or  $g$ 's  
 in the final state!

# Character of Proposed Experiments

- Sometime around 2008, Fermilab's possession of the energy frontier will end after 20 years.
- These experiments, CKM and BTeV, are both aimed at New Physics, but to study it, focus
  - on “the sensitivity frontier” --areas where rate and efficiency are more important than energy.
  - and (in BTeV's case) where the energy difference between the Tevatron and the LHC is not critical.
- These experiments make maximal use of our powerful existing facilities, **leveraging our investments without requiring upgrades, to do world class physics.**
- This should be viewed in the broader context of a program of “flavor physics” which includes the study of neutrino masses, mixing (MNS matrix), and CP violation.

**These experiments will address some of the most important problems in particle physics.**

# Experiment R&D

- The creation of a new experiment is now almost always a big task
  - At a mature machine whose energy is not growing, you are improving your reach by doing much harder experiments which may require
    - running at much higher luminosity
    - achieving much higher background rejection
  - This may in turn mean developing new kinds of detectors, triggers, or computing techniques or even new kinds of beamlines.
  - This also helps move technology forward, which is a way that we advance the capabilities of our field and contribute to society.

**The development of a sophisticated new experiment and the demonstration of its technical and scientific feasibility is in itself a significant research project and needs support, staffing, supervision, review, and *recognition*.**

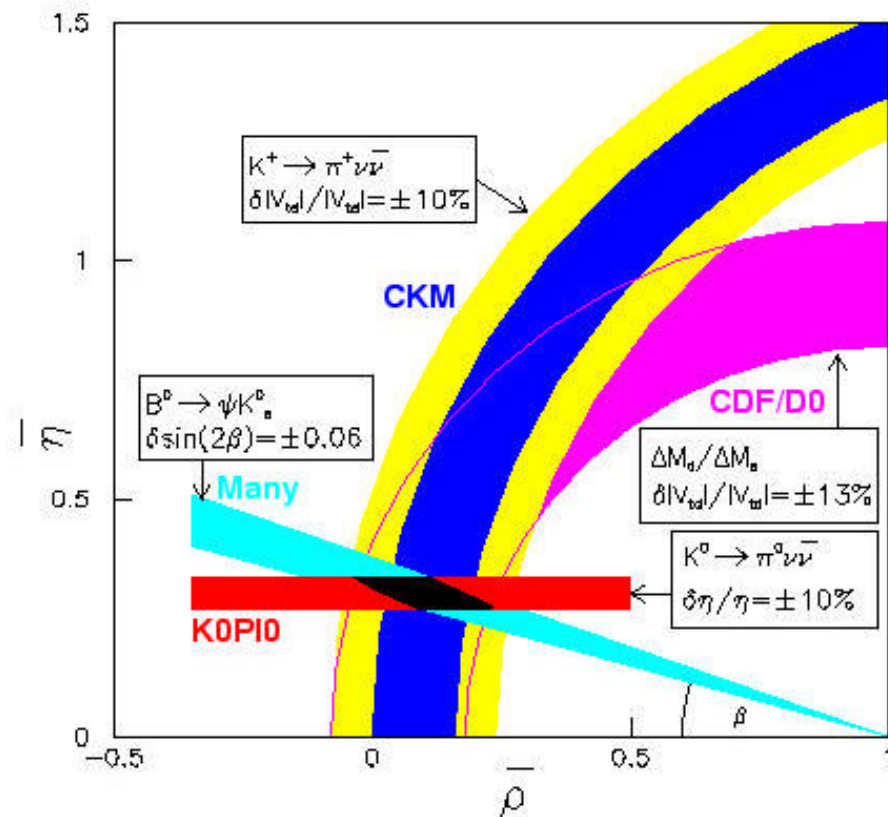
## CKM $\equiv$ Charged Kaons at the Main Injector

- CKM (E921) is an experiment to measure the ultra-rare kaon decay:  $K^+ \rightarrow \pi^+ \nu \nu$  to a branching fraction precision of 10%.
- This will measure the matrix element  $V_{td}$  with a statistical precision of 5% and an overall precision of 10%.
- CKM was approved as an R&D Project within the Particle Physics Division (E905) to develop a full proposal
- Subsequently, in summer of 2001, CKM received Stage 1 (scientific) approval from FNAL as E921.

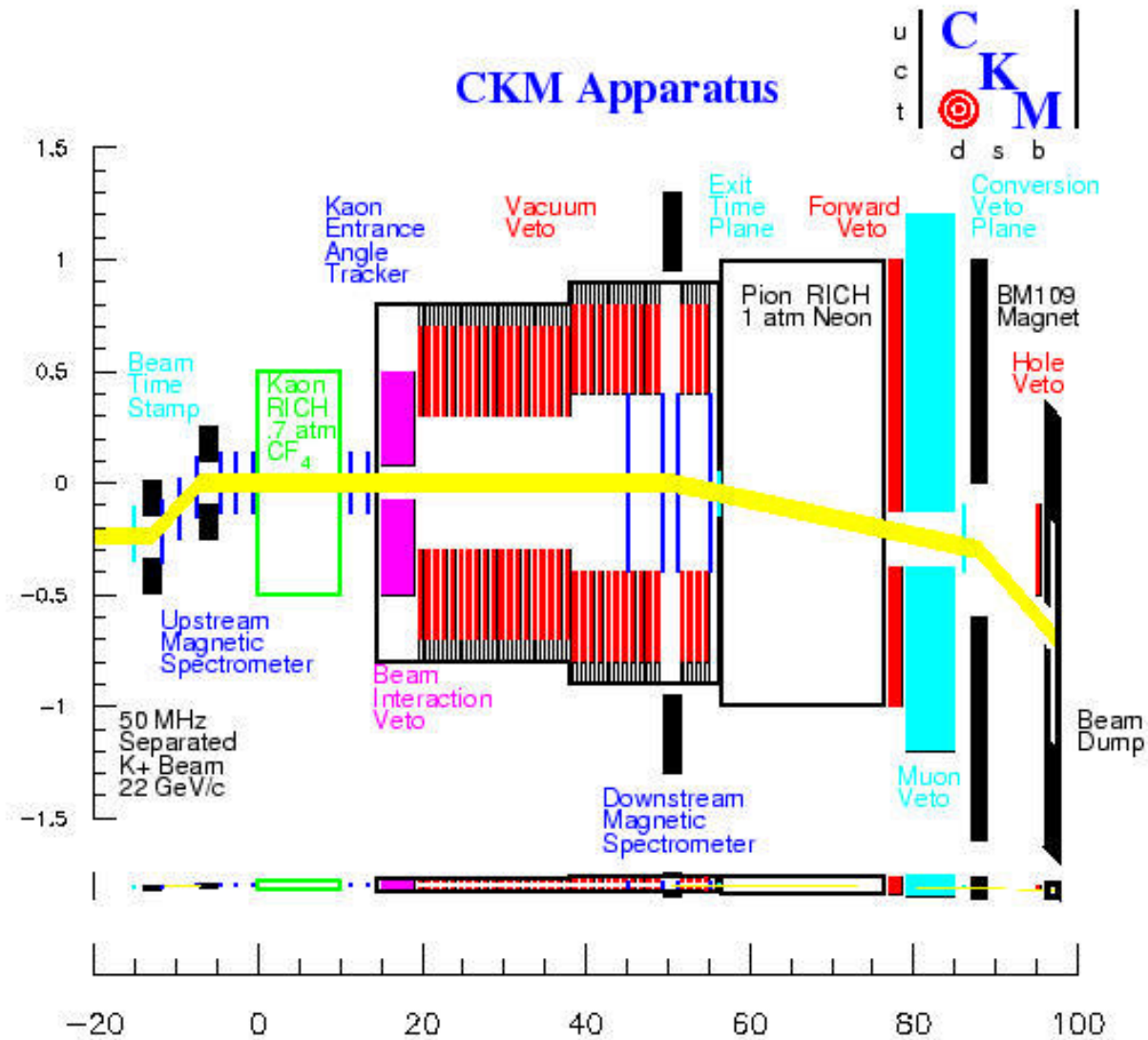
# $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ Data and Predictions

**Standard Model:**  $\text{Br}[K^+ \rightarrow \pi^+ \nu \bar{\nu}] = |V_{td}|^2 \times [\text{known stuff}] = [0.75 \pm 0.3] \times 10^{-10}$   
**BNL E787 (decay at rest)** has observed 2 events  $\text{B.R.} = [1.6^{+1.8}_{-0.8}] \times 10^{-10}$ .  
**This corresponds to about twice the SM value, but with large errors! Next step is a real measurement of this branching ratio to the limit of the theory**

The BNL effort, E949, is now running with an upgraded detector that can exploit the full AGS flux. With sufficient running E949 will get 5-10 SM events. **CKM, with ~100 events will make the definitive measurement.** **If the result stays high, and  $B_s$  mixing, which should be measured soon at FNAL, turns out to be even moderately higher than the present limit, say 25, there will be problems for SM!** Eleven physicists collaborate on both CKM and E949, including 4 members of the FNAL staff and 3 members of the BNL staff.

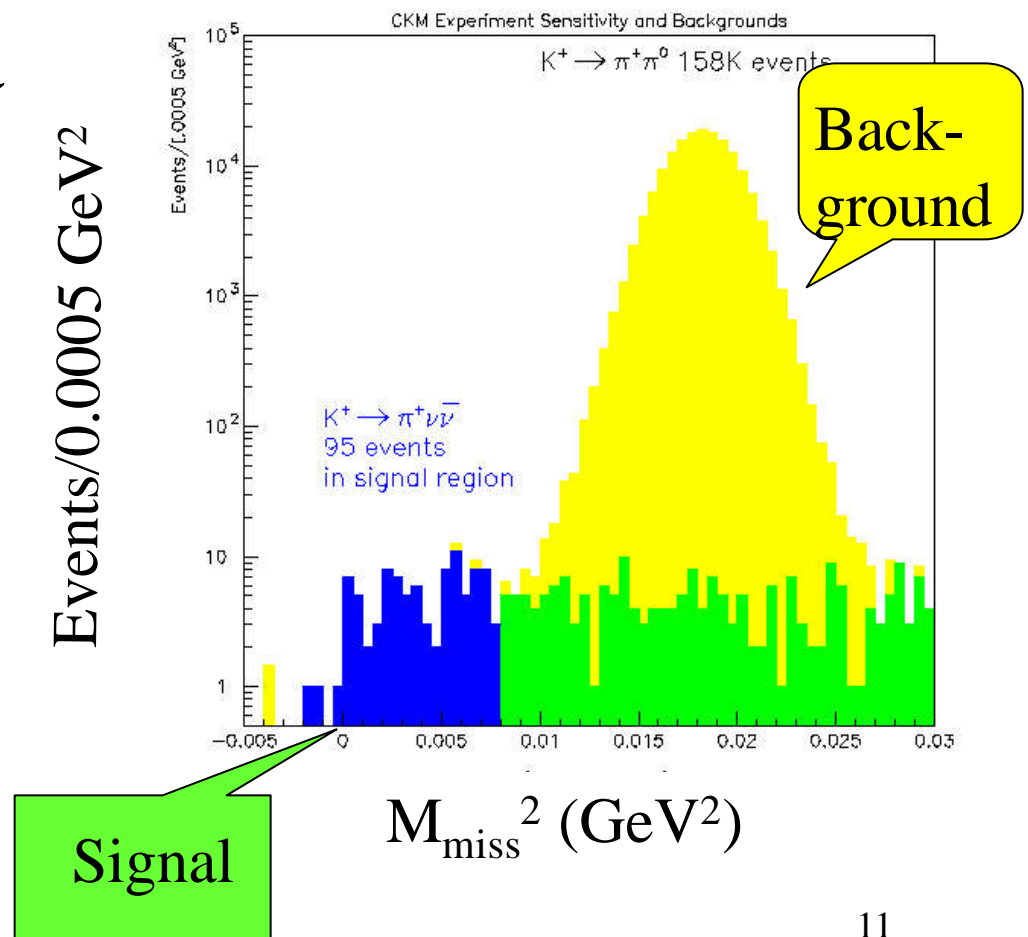


# The CKM apparatus uses proven detector technology



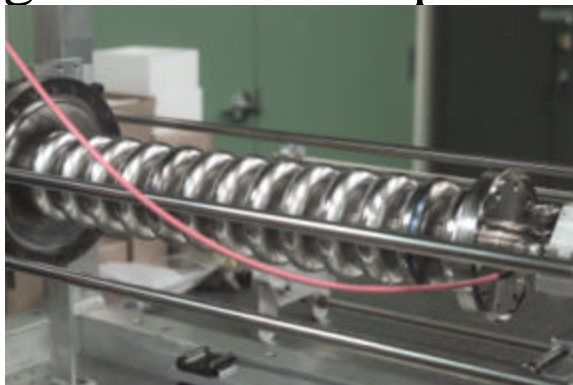
# Expected Signal and Background

- 95 signal events in a background free region
- $K^+ \rightarrow \pi^+ \pi^0$  is the main background
- 2 years of data taking is assumed



# RF Separated Beam

- CKM uses a decay in-flight technique -- key to get to higher rates
- CKM needs about 50 MHz separated charged Kaon beam at 22 GeV/c, with a purity of 2/1 and a momentum bite of 2%
- Solution is a super-conducting RF-Separated beam
  - ❑ R&D project in Beams Division with a goal of 5.7 MV/m, transverse field!
  - ❑ 13 cell niobium rf cavity at cryogenic temperatures
  - ❑ 3.9 GHz in TM110 mode, 26 cells/m, 3 cm iris
  - ❑ Two rf stations (6 13-cell cavities at each)
    - ➔ First one separates the pions and kaons in time
    - ➔ Second one deflects the kaons into the decay channel while absorbing the unwanted particles near axis



# CKM Highlights and Plans

- **Superconducting RF:** Following the success of the first 1-cell transverse field cavities, work is continuing on the fabrication and tuning issues of multi-celled cavities. The necessary infrastructure for characterizing multi-cell cavities is in place.
- **Straw based tracking in vacuum:** Two full length prototypes have been constructed and successfully tested in vacuum; the subtle mechanical issues are now understood in full; beam test at Fermilab in the fall
- **Very low mass beam trackers:** CKM is developing a full plane prototype of the low mass beam trackers to be tested at FNAL in the fall.
- **Photon Veto Technology:** A prototype module of the vacuum veto system is under construction for testing with 1 GeV electrons at JLAB and perhaps at Protvino. Goal is veto inefficiency of  $<10^{-5}$ .
- **Data Acquisition:** Studying a “triggerless” daq where data is piped directly from the detector ADCs/TDCs into a farm of software filters. Will use switches and data links somewhat similar to BTeV's,

# B Physics at Hadron Colliders

- **The Opportunity**

- The Tevatron, at  $10^{32}$ , produces  $10^{11}$  b-pairs per year
- It is a “Broadband, High Luminosity B Factory”, giving access to  $B_d$ ,  $B_u$ ,  $B_s$ , b-baryon, and  $B_c$  states.
- Because you are colliding gluons, it is intrinsically asymmetric so time evolution studies are possible (and integrated asymmetries are nonzero)

- **The Challenge**

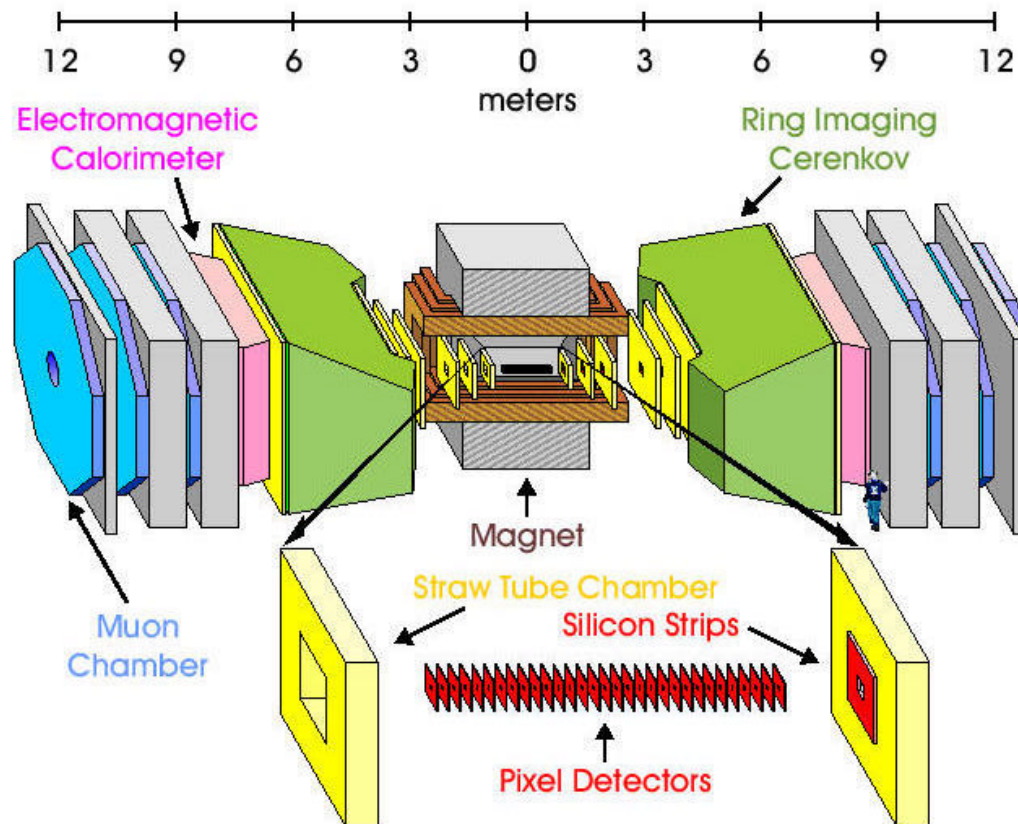
- The b events are accompanied by a very high rate of background events
- The b’s are produced over a very large range of momentum and angles
- Even in the b events of interest, there is a complicated underlying event so one does not have the stringent constraints that one has in an  $e^+e^-$  machine

These lead to questions about the triggering, tagging, and reconstruction efficiency and the background rejection that can be achieved at a hadron collider

# Requirements on “The Next Generation”

- Ability to run at high luminosity
- A very efficient trigger
- Superb vertex resolution
- An excellent particle identification
- A very high speed, high capacity data acquisition system
- Excellent photon/ $p^0$  reconstruction

## BTeV Detector Layout



# Key Design Features of BTeV

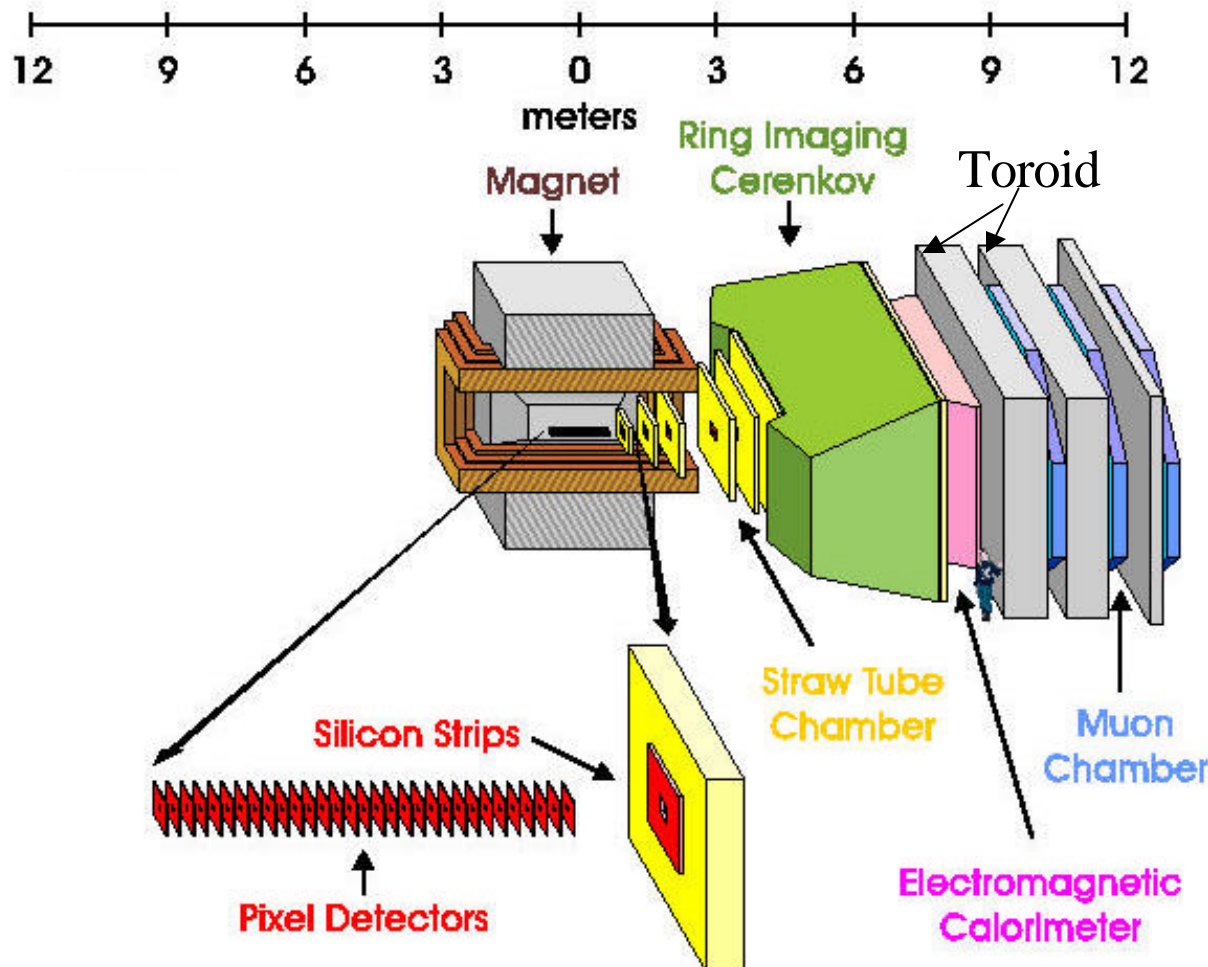
- A dipole located ON the IR, gives BTeV TWO spectrometers -  
- one covering the forward proton rapidity region and the other covering the forward antiproton rapidity region. **See following**
- A precision vertex detector based on planar pixel arrays
- A vertex trigger at Level I which makes BTeV especially efficient for states that have only hadrons. The tracking system design has to be tied closely to the trigger design to achieve this.
- Strong particle identification based on a Ring Imaging Cerenkov counter. Many states that will be of interest in this phase of B physics will only be separable from other states if this capability exists. It also allows one to use charged kaons for tagging.
- **A lead tungstate electromagnetic calorimeter for photon and  $p^0$  reconstruction**

# New Condition

- The budget situation has worsened since BTeV's initial Stage 1 approval by Fermilab
- To compensate, the experiment has been rescoped:
  - Only one arm will be instrumented, at least initially (sensitivity implications)
  - One option for the IR which is being developed involves constructing it from components liberated from the existing collider experiment IRs when one of them concludes (scheduling implications). Other options, which would have low cost and wouldn't interfere with operations, will also be developed.
  - Much of the offline computing hardware will be provided via using university resources made available over the network using grid software and relying on university and funding agency IT resources
- This lowers the cost by about \$70M to about a \$100M.
- This plan was recently presented to the FNAL PAC which reaffirmed the experiment's Stage 1 approval

# Reduced Scope BTeV Spectrometer

## BTeV Detector Layout



Since B's are produced by gluon-gluon fusion, both B's are boosted in the direction of the more energetic gluon, and go into the same arm. If this were not so, tagging would not be efficient with one Arm.

## Comparison to $e^+e^-$

- **At Snowmass, the E2 Working Group established that a  $10^{35}$  luminosity  $e^+e^-$  machine, the end point of upgrades to existing machines, had 1/10 the events as BTeV for  $B_d$  and  $B_u$  physics. BTeV is unrivalled for  $B_s$  or other B hadrons.**
- **It concluded that for  $e^+e^-$  to be competitive would require a machine capable of a luminosity of  $10^{36}$ !! This would not be an upgrade of PEP II but a new machine.**
- **BABAR would have to be completely rebuilt and much R&D would be needed to develop several high risk technologies**

# Comparison of a Single Arm BTeV with LHCb

Event Yields and Signal to Background for  $B^0 \rightarrow \rho\pi$

Mode	Branching Ratio	BTeV Yield	BTeV S/B	LHCb Yield	LHCb S/B
$B^0 \rightarrow \rho^{+/-} \pi^{-/+}$	$2.8 \times 10^{-5}$	5400	4.1	2140	0.8
$B^0 \rightarrow \rho^0 \pi^0$	$0.5 \times 10^{-5}$	776	0.3	880 “naïve, No backgnd	<0.05 My estimate

• BTeV is a factor of 2.5 better in raw yield and a factor of 4 when background dilution is accounted for. Unclear whether LHCb can even do  $B^0 \rightarrow \rho^0 \pi^0$  due to poor signal to background, but again would be a factor of four worse in effective number of events. LHCb cannot do c etc.

• BTeV's superior trigger, based on the pixel detector, and DAQ make it more able to follow new paths that may open up as more is learned

# BTeV Schedule

- BTeV could be built by 2008, with substantial portions in place by 2007.
- BTeV is designed so components can be installed on the fly a little at a time on collider down days. We can run low luminosity,  $10^{30}$ , collisions at the end of stores. We can debug detectors on flux from a wire target in the beam halo when collisions are not available. **We can be commissioned before the final IR is complete. This is worth at least a year, if not more.**
- The character of this physics is that it unfolds gradually as statistics are accumulated over a few years. In the end small differences in the starting time can be overcome by a superior detector. If we did start late w.r.t. LHCb, we have a sufficient advantage in some KEY states that we could rapidly catch up, e.g. 4x better in  $\rho$ - $\pi$ .
- We assume that the moment when the transition to BTeV will be made will be determined by physics considerations with due respect to the laws of statistics.
- Fermilab will begin to think about a “plan B” involving the construction of new magnets for C0, in case the physics of RUN 2 dictates that the two existing detectors continue.

# BTeV R&D Highlights and Plans

- **Pixel Detector:** achieved design (6-10 micron) resolution in 1999 FNAL test beam run. Demonstrated radiation hardness in exposures at IUCF. Will have a test of almost final readout chip in FNAL testbeam in 2002
- **Straw Detector:** prototype built, to be tested at FNAL in 2002
- **EMCAL:** two runs at IHEP/Protvino demonstrated resolution and radiation hardness. More tests in fall to verify stability of calibration system
- **RICH:** HPD developed and bench tested. Full test cell under development for beam test at FNAL in 2003
- **Muon system** tested in 1999 FNAL Test beam run. Better shielding from noise implemented and bench-tested. Design to be finalized in FNAL test beam in 2002
- **Silicon strip** electrical and mechanical design well underway
- **Trigger code** implemented on FPGA, Prototypes being constructed. NSF/RTES proposal approved to write fault tolerant software for massively parallel systems

Work supported by DOE/FNAL, DOE/University Program, NSF, INFN, IHEP, and others.

# BTeV Physics Reach - 1 Year

## at $2 \times 10^{32}$

Quantity	Uncertainty (s)
<b>b:</b> d sin2b	0.018
<b>a:</b> $B \rightarrow \rho p$	$4.3^\circ$
<b>g:</b> $B_s \rightarrow D_s K$ $B^- \rightarrow D^0 K^-$ $B^0 \rightarrow K \pi$	$8^\circ$ $14^\circ$ $7^\circ$ (plus theory)
<b>C:</b>  Sin( $2\chi$ )( $B_s \rightarrow J/\psi \eta^{(\prime)}$ )	0.03
<b>Other:</b> $\pi\pi$ asym $x_s (D_s \pi)$	0.034 up to 60

# Concluding Remarks

- **These experiments will make critical contributions to our knowledge of CP Violation as attention turns from initial observations to the work of finding out if the Standard Model explanation is correct and complete.**
- These experiments are not just doing Standard Model physics. They are **sensitive enough to reveal new phenomena.**
- **The R&D projects are critical to developing the technologies that will make these experiments possible. The work will insure that they will succeed and will increase the likelihood that they can be done on schedule and on budget. University groups play a key role**
- **Our field needs to show that we make the best use of existing facilities, that have received large investments, even as we seek, in the long term, new large facilities**
- **We must provide a diverse portfolio of large and small, domestic and foreign, accelerator and non-accelerator experiments, if we want to attract good students and provide them with good training --experiment design, detector R&D, computing and data analysis.**
- **Hopefully, these two experiments will form a key part of a world class flavor physics program, along with the neutrino program, after the LHC takes firm possession of the energy frontier.**